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(54) All fiber in-line optical isolator

(57) The present invention is directed at an all-fiber in line isolator. The basic isolator includes a single-mode optical fiber, a multimode waveguide, a coil or other traditional means to generate a magnetic field, and a fiber block or other traditional means to couple the fiber to the waveguide. In one embodiment, the fiber has a core and a cladding, and maintains a circular state of light polarization. The fiber has a coupling region where the cladding is partially removed. The waveguide evanescently couples to the fiber along the coupling region. The waveguide has magneto-optical properties such that applying a magnetic field along it causes backward propagating light to transfer to the waveguide with minimal disturbance to forward propagating light. Other embodiments using birefringent optical fibers are disclosed as well.

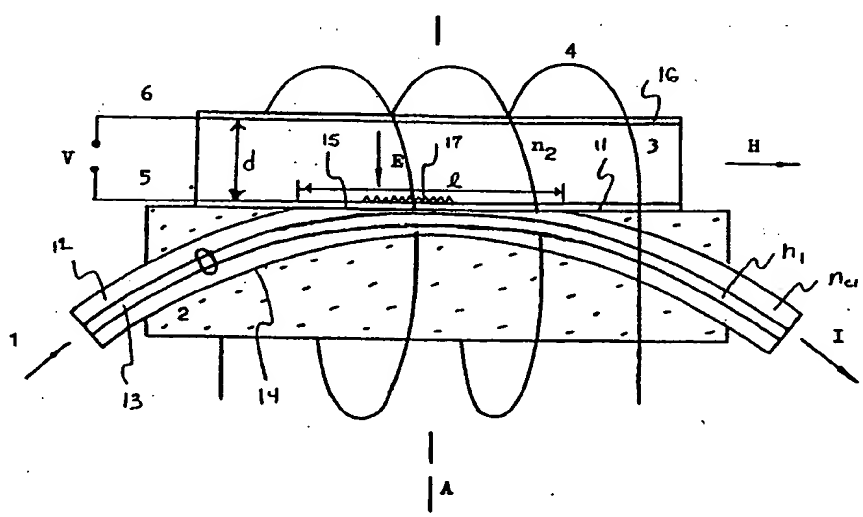

FIG. 1

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to an optical fiber device for use in communication and sensors. The device allows transmission of a light signal through an optical fiber in one direction, but prevents its propagation in opposite direction.

2. Information Disclosure Statement

Optical fiber components and sensors have become increasingly more important for effectively transmitting and processing signals in optical communication systems and many different optical fiber devices. Optical fiber systems essentially consist of at least one light transmitting optical fiber, a signal processing or sensor component, and a coherent radiation source (a laser). One of the most important tasks of many optical fiber systems is to prevent the light signal from reflecting back to the laser source. The properties of a laser can be greatly influenced by this undesired signal. This probl m is avoided using an isolator in the optical fiber circuit to transmit the light in one direction, but prevent its propagation in the opposite direction.

A frequently used optical fiber isolator consists of a bulk magneto-optical crystal affected by a magnetic field. The isolator is placed between two appropriately adjusted polarizers and optically connected between an interrupted optical fiber (see e.g., Laser Focus v. 14, No. 11, p. 52 (1978)). The use of an isolator in an integrated optical design which employs a waveguide is also known. The waveguide is produced from a magneto-optical film instead of a bulk crystal which reduces the magnitude of the control fields required (see e.g., US Patent No. 4,859,013).

Although these isolators are effective, they face several shortcomings. Traditionally, when using isolators of this type, the optical fiber is interrupted and the isolator spliced in line using butt-joint connections. The need to interrupt the optical fiber circuit and the optical losses associated with such an interruption are the main disadvantage of many known optical isolators. Another disadvantage is that these isolators are designed for a specific wavelength, and it is difficult to change their properties quickly when switching to another light wavelength.

All-fiber in-line isolators which employ Faraday rotation in a coil fabricated from birefrigent single-mode fiber plac d in a magnetic field (see J. Lightwav Techn.
v. 27, p. 56 (1084)) are also burdened with the need for xternal polarizers operating at some specific wavelength. A new kind of all-fiber in-line component based on an evanescent coupling between a single-mode fiber and a multimode planer waveguide has recently been investigated and used to design an all-fiber in line wavelength selective element and intensity modulator (see Electronics Lett. v. 28, p. 1364 (1992)). This device, however, cannot perform isolation functions.

OBJECTS AND SUMMARY OF THE INVENTION

The present invention is directed at providing a new and highly effective tunable all-fiber in line optical isolator. One object of the invention is to perform the isolation function without interrupting the optical fiber line. To accomplish this, the device evanescently couples the light propagating in a polarization maintaining single-mode optical fiber with a high refractive index multimode planar or rib type waveguide.

It is another object of this invention to provide a device which can be quickly tuned to compensate for varying wavelength of laser light. To perform this function, the waveguide comprises a material which exhibits magneto-optical and possibly electro-optical properties. A magnetic field is generated along the waveguide which alters the refractive indices for forward and backward propagating light. In one particular embodiment, electrodes are used to generate an electric field across the waveguide to provide for even greater control. Therefore, by using these fields, a user can effectively control the points at which the device isolates and transmits.

The above, and other objects, features and advantages of the present invitation will become apparent from the following description read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF DRAWINGS

Fig. 1 shows a schematic of an all-fiber in line optical isolator based on the fiber maintaining a circular polarization of light.

Fig. 2 shows the refractive index distribution in the cross section **A** of the system.

Fig. 3 shows the intensity of light transmitted through the isolator as a function of refractive index of the multimode waveguide overlay n_2, its thickness d, and the wavelength λ of the light.

Fig. 4 shows the fiber with a polished cladding and the rib multimode waveguide overlay.

Fig. 5 shows the refractive ind x distribution in the case when refractive index n_3
of the material over the multimode waveguide is greater than that of the fiber cladding.

Fig. 6 shows an embodiment which facilitates the transformation of polarization from a linear to a

circular state and then back again to a linear state using birefringent fibers.

Fig. 7 shows another embodiment using bir fringent fibers.

DESCRIPTION OF PREFERRED EMBODIMENTS

Figure 1 shows one particular embodiment of the present invention . A fiber 1 has a core 13 having a graded refractive index n_1 , and cladding 12 having a refractive index of n_{cl} . Fiber 1 guides laser light in single mode with a propagation constant of β_0 , and is manufactured to maintain a circular state of light polarization. For example, fiber 1 maintains a forward circular polarization as depicted in Figure 1.

Fiber 1 is held in place by a coupling means 2. In this embodiment, coupling means 2 is a special fiber block having a V-grove 14 which is shaped to provide a large radius bending of the fiber. Using a fiber block with a V-grove is well known in the art of butt-joining two fibers, fabricating all-fiber in line polarizers, and using X-type couplers for single-mode fibers (see, e.g., J.Dakin & B.Culshaw, Optical fiber sensors: Principles and Components (Artech House, 1988)). It can be fabricated, for example, with the help of silicon V-groove technology. The fiber block is polished to produce a polished surface 11 and to remove part of cladding 12 form fiber 1. By removing this cladding, a coupling region 15 of length l is formed along fiber 1. The thickness of the remaining cladding, i.e., the distance between the core/cladding boundary of the fiber and polished surface 11. is only a few microns.

Cladding of the fiber can also be partially removed from one side of the fiber without using the polishing technique. In one preferred embodiment one can employ, for example, a thermal evaporation process using, localized heating the cladding material by a focused beam from CO or CO_2 laser, whose focus position is controlled either manually or automatically. We have found experimentally that such a method permits to remove the cladding in desired region of the fiber to form a groove of prescribed shape. Control of position of the focus of the laser beam can be performed either manually or using automatic positioner controlled by computer in order to provide the desired shape of the groove. This method provides a possibility to remove fiber cladding on much longer distances than the fiber polishing technique and a possibility to control the shape of the grove and residual distance between fiber cor and surface of the cladding the most important param ters responsible for the light coupling between fiber core and a waveguide fabricated oil the fiber surface.

A waveguide 3 overlays the fiber block and fiber 1 along the polished surface 11. Waveguide 3 is a multimode type, possessing magneto-optical and possibly, electro-optical properties, and having a thickness d, a refractive index n_2 greater than n_{cl} , and a propagation constant β_n for its highest order mode. A crystal of bismuth silicate is an example of a possible waveguide material.

The refractive index profile of the composite system consisting of a waveguide 3 and fiber 1 in cross section A of Figure 1 is shown schematically in Figure 2 together with propagation constants of waveguide 3 and fiber 1. If the propagation constant β_0 of fiber 1 is matched to propagation constant β_n of waveguide 3 as it is shown is Figure 2-(a), then the light transfers from fiber 1 to waveguide 3. If however the propagation constants are not matched, then all the light energy remains in the fiber. As a result, the intensity, I, of the light transmitted by the fiber, shows typical resonance-like behavior as a function of the waveguide's refractive index n_2 , its thickness d, and the wavelength λ of the light (see Figure 3); since the mode propagation constant β_n is a function of these parameters. Referring to Figure 3; point 2 indicates an isolating point where all the light energy transfers from fiber 1 to waveguide 3. Point 1 indicates a transfer point where all the light energy remains in fiber 1. The device can be tuned to a specific transfer or isolating point by either polishing waveguide 3 to a certain thickness, varying the refractive index n_2 , or varying the wavelength λ.

A magnetic field means 4 generates a magnetic field H about waveguide 3 and coupling region 15. In this embodiment, magnetic field means is an electrical coil; however, other means are possible. Because of the Faraday effect in magnetic field H, the magneto-optical multimode waveguide 3 exhibits different magnitudes of refractive index n_2+ and n_2- for the circularly polarized light propagating in a forward and backward direction respectively. The refractive indices n_2+ and n_2- can be varied by the field H such that transfer point 1 corresponds to forward propagating light, and isolation point 2 corresponds to backward propagating light. Therefore, the magneto-optical properties of waveguide 3 can be adjusted so that the device works as an isolator. The present invention can change the direction of light transfer by simply changing the direction of the controlling magnetic field.

Tuning the device to an appropriate transmitting point and isolating point depending on the wavelength λ can also b conveniently and quickly realized by utilizing the electro-optical properties of waveguide 3. To this end, in one preferred embodiment a pair of thin transparent lectrodes 5 and 6 are embedded in waveguide 3 as shown in Figure

1. An electric field E is produced across waveguide **3** when a control voltage V is applied across electrode **5** and **6**. Due to the electro-optical effect the refractive index changes.

In the embodiment of Figure 1, waveguide **3** is planar, however, other preferred embodiments exist. For example, a rib waveguide **41**, as shown in Figure 4, may be desirable for certain applications. Rib waveguide **41** requires less voltage V to generate electric field E because of its narrower width. Furthermore, rib waveguide **41** has a better transverse field confinement compared to a planar waveguide.

If the refractive index n_3 of a material **16** over waveguide **3** is greater than refractive index n_{cl} of cladding **12** (as shown in Figure 5) due to technical reasons, then a grating **17** can be used (as shown in Figure 1). Grating **17**, located on coupling region **15**, is fabricated to match propagation constant β_0 to propagation constant β_n . Grating **17** may also be useful if it is desirable to switch one operating mode in the multimode waveguide to another in order to vary the properties of a particular isolator device as shown in Figure 5.

Fiber maintaining a circular state of polarization of the light used in this isolator device are well known. They can be fabricated, for example, by twisting a single-mode fiber in such a way as to induce tensions in the fiber which creates a difference in propagation constants for modes with forward and reverse circular polarizations. This prevents a coupling between these two polarization states. In some practical applications, another type of polarization maintaining single-mode fiber is us d, namely the birefringent fiber. These fibers are characterized by an elliptic core or a PANDA-type configuration. Such fibers were designed to transmit the light with a linear state of polarization. The present invention may easily be modified to incorporate these fibers.

The modification is shown in Figure 6. Three sections from the same birefringent single-mode fiber - an input fiber **61**, an intermediate fiber **62** and an output fiber **63** - are butt-joined together with the help of V-groove technology in a coupling means **64**. A birefringent fiber is characterized by two orthogonal axis of symmetry corresponding to the orthogonal polarization states which are maintained as the light propagates through the fiber. Each fiber has a specific relative orientation of its polarization axis of symmetry, and intermediate fiber **62** has a polarization beat length L. The axis of symmetry of intermediate fiber **62** is turned over a $\pi/4$ angl with respect to the axis of symmetry of input fiber **61**. The axis of symmetry of output fiber **63** is turned over a $\pi/2$ angle relative the axis of the input fiber **61**. If length l is chosen to be equal to $\pi/\Delta\beta$, wh r in $\Delta\beta$ is the difference between the propagation constants corresponding to two orthogonal states of polarization of the birefringent fiber, then intermediate fiber **62** has a circular state of polarization in its middle. Parameters of the birefringent fiber must be chosen in such a way that beat length L is much greater than the length l of the coupling region **65** (see Figure 6).

Another embodiment of the present invention also incorporates birefringent fibers, As shown in Figure 7, this embodiment employs a coupling means **75** (in this embodiment a fiber block), an input fiber **71**, an output fiber **72**, an intermediate region **73**, a waveguide **76**, a polarizer **74**, and magnetic field means **90**, (in this embodiment a coil). Coupling means **75** has a coupling region **81** which is much longer than in the other embodiments of the invention (see, e.g., Figure 6). Input fiber **71** has a proximate end **86**, a distal end **88** and a length l_1 along coupling region **81**. Output fiber **72** has a proximate end **87**, a distal end **89**, and a length l_2 along coupling region **81**. Each fiber also has a specific relative orientation of its polarization axis of symmetry. The axis of symmetry of input fiber **71** at proximate end **86** is perpendicular to the plane of coupling region **81**, and the axis of output fiber **72** at its proximate end **87** is turned over a $\pi/4$ angle with respect to the axis of input fiber **71** at its proximate end **86**.

Intermediate region **73** is between proximate end **86** and proximate end **87** and has a length l_3 along coupling region **81**. Intermediate region **73** is filled with an immersion material whose refractive index must not be higher then refractive index n_{cl} of the fiber cladding **12**. A section of the same fiber as **71** and **72** can also be used is intermediate region **73**.

Because of the Faraday rotation inherent in a magnetic field H, the polarization of forward propagating light call be rotated at an angle of $\pi/4$ along length l_3 in waveguide **76** by choosing the appropriate field strength H. The light is then coupled to output fiber **72** along length l_2. Length l_3 is much greater than l_1 or l_2
so that the Faraday rotation at the distances l_1 and l_2 may be neglected. The polarization of the backward propagating light rotates an additional $\pi/4$ as it propagates back through waveguide **76**. Therefore, the total rotation of the polarization of the backward propagating light with respect to the polarization of incoming forward propagating light in the region of proximate end **86** becomes $\pi/2$.

A polarizer **74** is located at the boundary between coupling region **81** and waveguide **3** as it is shown in Figure 7. Polariz r **74** may be fabricat d as a strip of thin metallic film. If the light in input fiber **71** is polarized such that the direction of its electric field is perpendicular to coupling region **81**, then after coupling to the high st order mode of

waveguide **76**, along length l_1, the fight propagates through polarizer **74** with practically no attenuation. However, if the polarization of the light is rotated over the angle $\pi/2$, then light is attenuated by polarizer **74** because its electric field is parallel to the plane of polarizer **74**.

The electrodes **77**, **78**, and **79**, **80** may be used to control the transfer of light across the boundary between waveguide **76** and the input/output fibers electro-optically, and also electrodes **91** and **92** can be used to support all adiabatic regime which avoids abrupt changes of mode propagation between different regions of the waveguide. Furthermore, a rib waveguide may be used as described before. A rib waveguide reduces the controlling voltages V_1, V_2, and V_3, and improves the transverse field confinement in the overlay waveguide.

Having described preferred embodiments of the invention with reference to the accompanying drawings, it is to be understood that the invention is not limited to the precise embodiments, and that various changes and modifications may be effected therein by skilled in the art without departing from the scope or spirit of the invention as defined in the appended claims.

Claims

1. An all-fiber in line isolator for isolating backward propagating light from forward propagating fight, said isolator comprises:
   a. an optical single-mode fiber, said fiber has a core having a refractive index n_1 and a cladding having a refractive index n_{cl}, said fiber maintains a circular state of light polarization; said fiber has a coupling region wherein said cladding is partially removed:
   b. an optical multimode waveguide, said waveguide has parameters including a thickness d and a refractive index n_2, said refractive index n_2 is grater than said refractive index n_{cl}, said waveguide made from magneto-optical material that exhibits different magnitudes of refractive index n_2 + and n_2 - for circularly polarized light propagating in forward and backward directions respectively such that applying a magnetic field H along said waveguide and said coupling region facilitates a transfer of backward propagating fight from said fiber to said waveguide with a minimal disturbance to forward propagating light, said parameters are chosen to effect a desired transfer point;
   c. coupling means for evanescently coupling said coupling region to said waveguide; and
   d. magnetic field means for applying said magnetic field H along said waveguide and said coupling region.

2. The device of claim 1 wherein said waveguide comprises electro-optical properties such that said transfer point depends upon the intensity of an electric field E applied across said waveguide and coupling region thereby facilitating tuning of said transfer point; and the device further comprises:
   e. electric field means for applying said electric field E across said waveguide and coupling region

3. The device of claim 1 further comprising:
   e. a grating, said grating is mounted to said coupling region of said fiber, said grating matches the propagation constant of backward propagating light in said fiber to the propagation constant of backward propagating light in said waveguide to effect said transfer point.

4. An all-fiber in line isolator for isolating backward propagating light from forward propagating light, said fiber comprises:
   a. at least three birefringent single-mode optical fibers, an input fiber, an intermediate fiber, and an output fiber, each fiber has a core having a refractive index n_1 and a cladding having a refractive index of n_{cl}, each fiber maintains a linear state of light polarization, said intermediate fiber has a coupling region of length l wherein said cladding is partially removed, said intermediate fiber has a polarization beat length L which significantly exceeds said length l and is half the length of said intermediate fiber, each fiber has an orientation of polarization axis of symmetry, said axes of symmetry are successively rotated by an angle of $\pi/4$ relative to all adjacent fiber thereby generating a circular state of light polarization in said coupling region:
   b. an optical multimode waveguide, said waveguide has parameters including a thickness d and a refractive index n_2, said refractive index n_2 is greater than said refractive index n_{cl}, said waveguide has magneto-optical properties such that applying a magnetic field H along said waveguide and said coupling region facilitates a transfer of backward propagating light from said fiber to said waveguide with a minimal disturbance to forward propagating light, said parameters are chosen to effect a desired transfer point;

c. coupling means for holding said fibers in position and for evanescently coupling said coupling region to said waveguide;
and
d. magnetic field means for applying said magnetic field H along said waveguide and said coupling region.

5. The device of claim 4, wherein said waveguide comprises electro-optical properties such that said transfer point depends upon the intensity of an electric field E applied across said waveguide and coupling region thereby facilitating tuning of said transfer point; and the device further comprises:
   e. electric field means for applying said electric field E across said waveguide and coupling region.

6. The device of claim 4 further comprising:
   e. a grating, said grating is mounted to said coupling region of said fiber, said grating matches the propagation constant of backward propagating light in said fiber to the propagation constant of backward propagating light in said waveguide to effect said transfer point.

7. All all-fiber in line isolator for isolating backward propagating light from forward propagating light, said isolator comprises:
   a. at least two birefringent optical fibers, an input fiber and an output fiber, each fiber has a distal end, a proximate end, a core, and a cladding having a refractive index of n_{cl} , each fiber guides light in a linear state of polarization, said proximate ends of said input and output fibers comprise a coupling region along lengths l_1 and l_2 respectively wherein said cladding is partially removed, each fiber has a_specific orientation of polarization axis of symmetry, said axis of said input fiber is perpendicular to the plane of said coupling region, said axis of said output fiber is turned over the angle of $\pi/4$ relative to plane of said coupling region and over the_angle of $\pi/2$ relative to said axis of said input fiber;
   b. an optical waveguide, said waveguide has magneto-optical properties and parameters which include a thickness d and a refractive index n_2 being greater than said refractive index n_{cl} , said parameters are chosen to facilitate a transf r of forward and_backward propagating light from said fibers to said waveguide.
   c. coupling means for evanescently coupling said fibers to said waveguide, for supporting said fibers, and for defining an intermediate region between said proximate ends of said input and output fibers, said intermediate region has a length l_3 , said length l_3 is much greater than said lengths l_1 and l_2.
   d. an immersion material, said intermediate region contains said immersion material, said immersion material has a refractive index not greater than said refractive index n_{cl} .
   e. magnetic field means for applying said magnetic field H along said coupling region, said magnetic field H rotates the polarization of forward propagating light in said intermediate region by an angle of $\pi/4$ relative to said coupling region, said magnetic field H further rotates the polarization of backward propagating light in said intermediate region by an additional angle of $\pi/4$ for a total rotation of $\pi/2$ relative to the light polarization in said input fiber [said coupling region; and
   f. a polarizer, said polarizer interfaces between said coupling region and said waveguide, said polarizer transmits forward propagating light having its polarization perpendicular to the plane of said polarizer and absorbs backward propagating light having its polarization rotated by an angle of $\pi/2$ relative to the plane of said polarizer.

8. The device of claim 7, wherein said waveguide comprises electro-optical properties such that said transfer point depends upon the intensity of an electric field E applied across said waveguide and coupling region thereby facilitating tuning of said transfer point; and the device further comprises:
   g. electric field means for applying said electric field E across said waveguide and coupling region.

9. The device of claim 7, wherein said waveguide has magneto-optical properties.

10. The device of claim 13 further comprising:
   g. a grating, said grating is mounted to said coupling region of said fibers, said grating matches the propagation constant of light in said fiber to propagating constant of light in said waveguide to effect said transfer point.

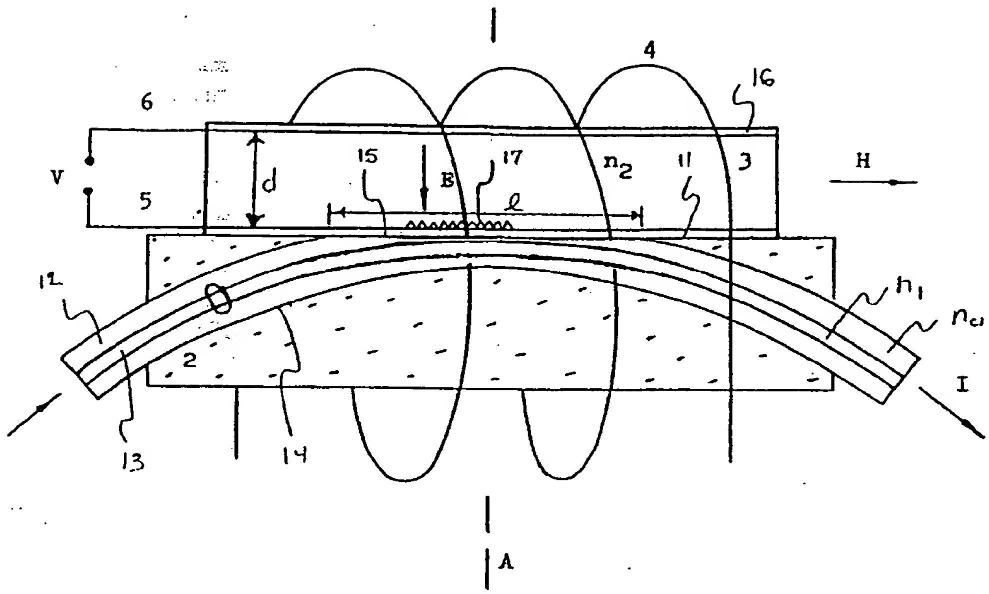
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FIG. 1

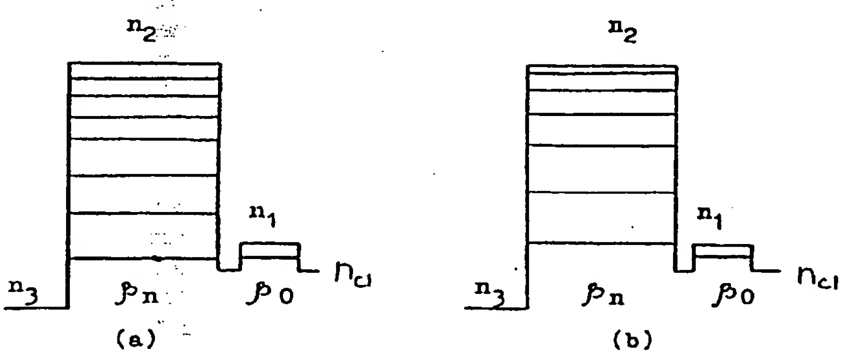
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Fig.2

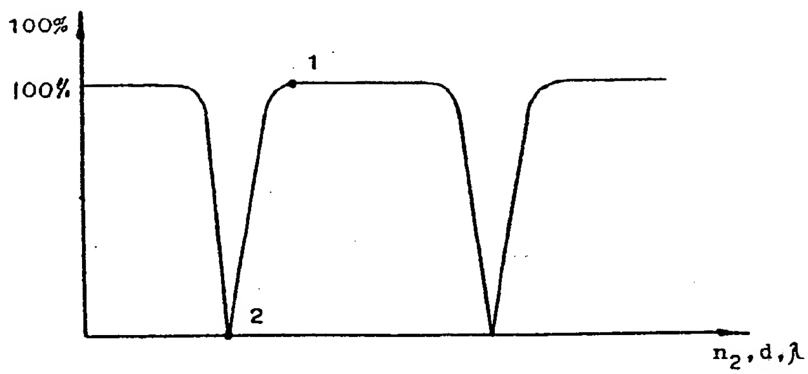


Fig.3

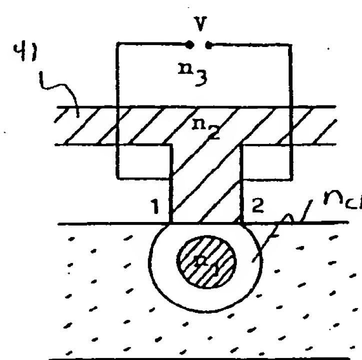


Fig.4

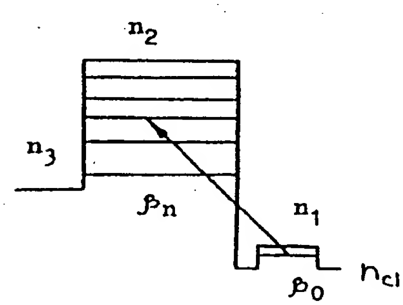


Fig.5

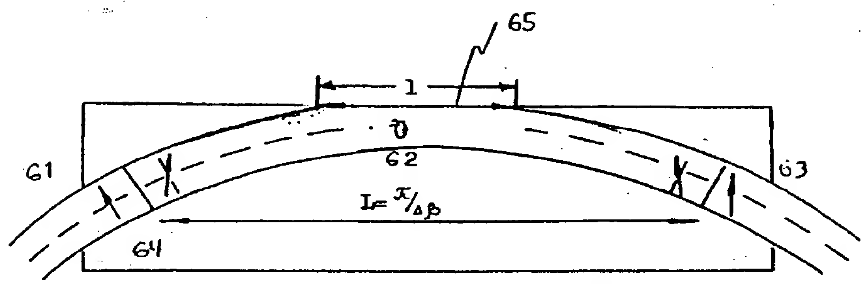
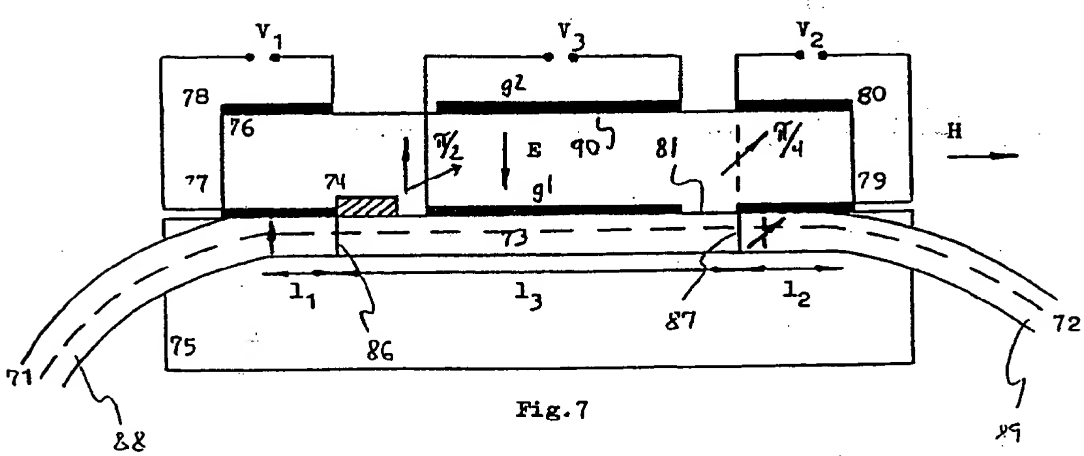

65
1
62
61
63
L= π/Δβ
64

Fig.6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l3
l2
87
72
75
86
71
88
89

Fig.7

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 95 20 1516

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	**Citation of document with indication, where appropriate, of relevant passages**	**Relevant to claim**	**CLASSIFICATION OF THE APPLICATION (Int.Cl.6)**
A	ELECTRONICS LETTERS., vol.29, no.1, 7 January 1993, STEVENAGE GB pages 104 - 105 V. PRIYE AND M. TSUTSUMI 'NONRECIPROCAL BEHAVIOUR OF LEAKY GYROTROPIC WAVEGUIDE' * the whole document * ---	1,4,7	G02F1/095
A,D	ELECTRONICS LETTERS., vol.28, no.14, 2 July 1992, STEVENAGE GB pages 1364 - 1365 W. JOHNSTONE ET AL. 'FIBRE OPTIC WAVELENGTH CHANNEL SELECTOR WITH HIGH RESOLUTION' * the whole document * ---	1,4	
A	TRANSACTIONS OF THE INSTITUTE OF ELECTRONICS AND COMMUNICATION ENGINEERS OF JAPAN, SECTION E, vol.E73, no.4, April 1990, TOKYO JP pages 474 - 476 T. SHINTAKU AND T. UNO 'Directional Coupler Type Optical Circulator' * the whole document * ---	1,4	**TECHNICAL FIELDS SEARCHED (Int.Cl.6)** G02F G02B
A	US-A-3 990 777 (AURACHER) * column 2, line 57 - column 3, line 47 * * figure 3 * ---	1,4	
A	EP-A-0 296 676 (PHILIPS) * column 3, line 1 - line 23 * * figure 1 * ---	1,4	
A	EP-A-0 112 223 (THOMSON) * claim 1 * --- -/--	1,4	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	28 July 1995	Luck, W

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

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EUROPEAN SEARCH REPORT

Application Number
EP 95 20 1516

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	PATENT ABSTRACTS OF JAPAN vol. 17, no. 372 (P-1573) 12 March 1993 & JP-A-05 061 002 (MATSUSHITA) * abstract * -----	7	

TECHNICAL FIELDS SEARCHED (Int.Cl.6)

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